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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 485

A COMPARISON OF SEVERAL METHODS OF MEASURING IGNITION LAG  
IN A COMPRESSION-IGNITION ENGINE

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Washington  
January 1934

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A COMPARISON OF SEVERAL METHODS OF MEASURING IGNITION LAG  
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SUMMARY

The ignition lag of a fuel oil in the combustion chamber of a high-speed compression-ignition engine was measured by three different methods. The start of injection of the fuel as observed with a Stroborama was taken as the start of the period of ignition lag in all cases. The end of the period of ignition lag was determined by observation of the appearance of incandescence in the combustion chamber, by inspection of a pressure-time card for evidence of pressure rise, and by analysis of the indicator card for evidence of the combustion of a small but definite quantity of fuel.

A comparison of the values for ignition lags obtained by these three methods indicates that the appearance of incandescence is later than other evidences of the start of combustion, that visual inspection of a pressure-time diagram gives consistent and usable values with a minimum requirement of time and/or apparatus, and that analysis of the indicator card is not worth while for ignition lag alone.

INTRODUCTION

At the present stage of the development of the high-speed compression-ignition engine considerable attention is being given to methods of rating fuel oils as to their suitability for use in such engines (references 1-5). It is generally recognized that there is a definite connection between the ignitibility of fuel oil and its satisfactory operation in an engine. As a measure of ignitibility the length of the period of delay between the injection and the ignition of the fuel has been used, but no method as yet devised for the measurement of this period can be considered as universally satisfactory and acceptable.

Ignition lag in a compression-ignition engine is most satisfactorily defined as the interval between the start of injection of fuel and the point at which the pressure in the engine cylinder measurably exceeds the compression or expansion pressure without ignition. Ignition lag may thus be measured in time units or it may be more conveniently expressed in degrees of crankshaft rotation.

The use of ignition lag as a measure of the ignitibility of a fuel requires that the limits of the period of ignition lag be so defined that there will be no doubt as to just what part of the operating cycle is included by this term. There seems to be a general agreement that the period of ignition lag begins with the entrance of the first particle of fuel into the combustion chamber. The end point of the period of ignition lag is determined by a variety of methods depending upon the equipment available in the laboratories where the work is done and, although there is a lack of agreement in absolute values, there is excellent similarity in comparative values.

Some of the devices used to determine the start of the ignition lag are an electrical contact in the combustion chamber closed by the impact of the entering fuel, mechanisms which record the rise of pressure in the injection tube or the movement of the injection valve stem, and stroboscopic apparatus that allows a visual determination of the start of the spray with respect to the position of some part of the test engine, usually the flywheel.

The determination of the end of the period of ignition lag depends upon the investigator's conception of what constitutes effective ignition. At this laboratory three methods have been used at different times to detect effective ignition taking as evidence of the start of combustion (a) the appearance of incandescence in the combustion chamber, (b) the occurrence of perceptible combustion pressures on an indicator card, and (c) the determination of the effective combustion of a small but definite fuel quantity by analysis of the indicator card.

Previous work at this laboratory had shown that at fixed engine-operating conditions the time at which incandescence first appears in the combustion chamber of a compression-ignition engine is quite definite and constant. Most of the investigators of the self-ignition temperatures of fuels agree that some combustion occurs before inflammation, but investigators who use windows in combustion

chambers of spark-ignition engines find such a close relationship between the progress of the flame front and the rise of pressure in the cylinder that inflammation is considered to be simultaneous with the start of combustion. If this close relationship occurs also in the compression-ignition engine the appearance of incandescence in the combustion chamber may be used as evidence of ignition of the fuel.

When the indicator card is used to detect the occurrence of effective ignition the determination depends upon the accuracy and sensitivity of the pressure indicator. Effective ignition is generally considered to occur at the point where the pressure line with combustion diverges from the pressure line without combustion and is commonly designated "the breakaway point." The pressure line without combustion, but with operating temperatures in the cylinder, is different from the motoring pressure line with comparatively low temperatures in the cylinder. A pressure diagram with the higher cylinder temperatures but without ignition at the usual place may be obtained by operating the engine with retarded injection.

Gerrish and Voss (reference 6), by considering that combustion starts when the pressure rise has shown that a small but definite quantity of fuel has been burned, are able to get consistent trends from the analysis of indicator cards that would give inconsistent results if the combustion were assumed to start at the last point where no burning could be detected.

The series of engine tests reported herein were made in the N.A.C.A. Laboratory at Langley Field, Va., during March 1932, and were used for a comparison of the three methods outlined above for the determination of the ignition lag of a fuel oil in a compression-ignition engine.

#### APPARATUS AND TEST PROCEDURE

This investigation was made with a single-cylinder test engine equipped with an N.A.C.A. cylinder head no. 4 having a vertical-disk form of combustion chamber. This engine as equipped with the special apparatus for obtaining the necessary data is shown in figure 1. The apparatus includes the disk stroboscope (A) suspended over the engine and driven from the exhaust camshaft of the engine

by a flexible shaft (B), the Farnboro indicator pressure element (C) connected by wire and tube to the recording mechanism (not shown), a quartz glass window (D) with its reflecting mirror (E), a Stroborama projector (F) for illuminating the index (G) painted on the engine flywheel and pointing to a scale (H) graduated in degrees of crankshaft rotation. Figure 2 shows the method by which it was possible to observe simultaneously the incandescence in the engine cylinder and the position of the flywheel as illuminated by the flash of the Stroborama.

The engine-operating conditions are listed in table I. For the tests with variable injection advance angle the same pump control settings were used and the variation in fuel quantity with change of injection advance angle was too small to affect the data as used. Pressure-time diagrams were taken with the Farnboro indicator as modified at this laboratory, photographic prints of the records being used for the analysis. The recording drum was rotated at crankshaft speed.

The start of fuel injection was determined by observing the first appearance of fuel at the tip of the injection valve nozzle by means of the Stroborama and the timing was fixed by simultaneously noting the flywheel position. This observation was made while injecting the fuel into the atmosphere, as previous injecting into a pressure chamber had shown no variation in timing with the density rising to 1.5 pounds per cubic foot. This determination could be reproduced within one half crankshaft degree.

Some preliminary tests were made to determine the best technic for obtaining the reading of the first appearance of incandescence. After the engine had reached stabilized operating temperatures, it was stopped and the quartz window was inserted as quickly as possible. Engine operation was immediately resumed and the observer brought the first part of the incandescent period into phase with the opening of the slot in the stroboscope. The Stroborama flash was synchronized with the first appearance of incandescence by remote control and the position of the flywheel noted. Any one observer could repeat observations within 1°.

Tests were made to determine whether the field of view from the small window was so restricted that inflammation might occur in any portion of the chamber and not be visible. A fuel quantity that reduced the scale load-

ing from 22 to 21 pounds while motoring the engine was sufficient to produce an unmistakable flash lasting about 35 crankshaft degrees. This fuel quantity, estimated to be 0.000005 pound per cycle, air-fuel ratio about 1,000, should theoretically reach enough air to burn completely within 1-1/4 inches of the nozzle. Apparently any fuel quantity that would operate the engine would produce sufficient incandescence for these tests.

Tests with increasing fuel quantity at a constant injection advance angle showed that the start of incandescence was well defined and constant at fuel quantities between 0.00014 and 0.00019 pound per cycle. Below this range there was slightly more variation in the start of incandescence and above it the window had to be cleaned too frequently. The window could be used for more than 20 minutes at a fuel quantity of 0.00015 pound per cycle without introducing an error due to the sooting of the window. The absence of change in the time of the appearance of incandescence over a wide range of fuel quantity per cycle is an indication that the observation is not materially affected by the spatial distribution of the flame and that the position of the window does not prevent the observer from detecting incandescence in parts of the combustion chamber not directly in the field of view through the window.

The data were then procured for the comparison of the three methods of measuring ignition lag. A fuel quantity of approximately 0.00015 pound per cycle (air-fuel ratio about 32) was used and the injection advance angles were varied in 2° intervals from 16° B.T.C. to 6° A.T.C. Indicator cards were taken and the first appearance of incandescence recorded for each injection advance angle. The pressure-time curves are shown combined in figure 3 with the start of incandescence marked on each curve. An analysis of these curves for effective fuel burned gives the series of curves shown in figure 4. The high-pressure sections of four of the indicator cards are shown in figure 5. These data are considered well suited for a comparison of the different methods on account of the short ignition lag and the comparatively large effect of any variation or errors in measurement.

## RESULTS AND DISCUSSION

The ignition lags as obtained from the data are listed in table II. The columns 2 to 6, inclusive, are the individual determinations by visual inspection of the indicator card of five engineers experienced in engine testing. The seventh column is an average of the five values for each injection advance angle. The eighth column lists the ignition lags obtained when the first appearance of incandescence is considered as marking the start of combustion. The last column shows the values obtained by considering that combustion has started when a small but definite amount of fuel has been effective in raising the pressure in the cylinder. No two series of values were determined by the same person. It should be noted that the ignition lags as determined by any of these methods remain virtually constant over the normal operating range and increase at both ends of this range so that the ignition lag both decreases and increases with increase in injection advance angle.

At the time this work was started it was hoped that the first appearance of incandescence would fix a comparatively definite point that would show the start of combustion in the engine cylinder, but after preliminary observations it was realized that the appearance of the visible flame is a comparatively gradual process. The time of appearance of incandescence in the combustion chamber was surprisingly late because in all cases it occurred after the pressure-time record had shown a definite pressure rise (fig. 3). Therefore, it is obvious that the appearance of incandescence is of little value in establishing the start of combustion in a compression-ignition engine because it occurs later than other evidences of the start of combustion. However, the values of the ignition lag obtained by using the appearance of incandescence as the starting point of combustion follow the same trend as the values obtained by using the start of pressure rise but with a smaller variation.

The method of measuring ignition lag by using the breakaway point or start of pressure rise as the termination of the period of lag is open to the objection that the determination may not be reproduced by different observers. A measure of the consistency in determining the breakaway point may be obtained by comparing the individual determination of the five observers with the average

of their determinations. Of the 60 values listed in table II, 22 agree with the average, 18 are within  $1/2^\circ$ , and 16 are within  $1^\circ$ , leaving only 4 in excess of  $1^\circ$ . Two thirds of the total determinations are within a range of 1 crankshaft degree and practically all are within  $\pm 1^\circ$ . Thus, it appears that this method is sufficiently accurate and consistent to give good comparative values but not necessarily exact values for ignition lag. The values obtained by this method show a greater variation than the values obtained by either of the other methods.

The values for ignition lag obtained by considering combustion as starting when a small but definite quantity of fuel has been burned are possibly more definite than values obtained by other methods, but in this case they are lacking in contrast as ten consecutive values cover a range of only  $1^\circ$  and therefore indicate that the ignition lag remains virtually constant over a range of  $20^\circ$  of injection advance angle.

A comparison of the three sets of values for ignition lag indicates that the values obtained from direct inspection of the indicator card by experienced observers are consistent and have the advantage of requiring no extra apparatus and a minimum of time. The appearance of incandescence in the combustion chamber of a compression-ignition engine is of doubtful value for determining when combustion starts. The ignition lags obtained from analyses of the indicator cards were apparently not of sufficient value to justify the expenditure of time required by this method. These results indicate that it will be quite difficult to have agreement in values for ignition lag between different laboratories or even between different experimenters until apparatus and methods are standardized.

Langley Memorial Aeronautical Laboratory,  
National Advisory Committee for Aeronautics,  
Langley Field, Va., November 14, 1933.



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TABLE I

## Test Apparatus

Engine	N.A.C.A. Universal test engine	
Cylinder head	"	No. 4
Fuel injection pump	"	No. 7
Fuel injection valve	"	No. 13

## Engine Operating Conditions

Engine speed	1,500 r.p.m.
Full load fuel quantity	0.000325 lb./cycle
Fuel quantity used in tests	0.00015 "
Injection period used in tests	12° (crank)
Injection advance angle	Variable
Injection nozzle type	6 orifices in single plane
Fuel valve position	Top hole of cylinder head
Valve-opening pressure	3,000 lb./sq.in.
Compression ratio	15
Temperature cooling water (out)	170° F.
Temperature lubricating oil (out)	140° F.
Temperature fuel oil	85° F.
Temperature inlet air	65° F.
Barometer	30.26 in.Hg
Engine valve timing	<div style="display: flex; align-items: center;"> <div style="font-size: 4em; margin-right: 10px;">{</div> <div> Inlet : opens 38° B.T.C.            closes 27° A.B.C.  Exhaust: opens 36° B.B.C.            closes 25° A.T.C. </div> </div>

TABLE II

## Ignition Lag

(All values given in degrees of crankshaft rotation at 1,500 r.p.m. For time values multiply by 0.000111 sec.)

Injection advance angle	Direct observation of card						Start of incandescence	Card anal. Fuel quan. $4 \times 10^{-6}$ lb.
	Observers					average		
	A	B	C	D	E			
A.T.C. 6	16	15	15	14	13	14+	16+	12.4
4	13	12	11	12	12	12	16	10.2
2	10	12	11	11	12	11	15+	10.5
T.C.	8+	8	7	9	8	8	13	9.7
B.T.C. 2	7	8	8	8	7	7+	11	9.7
4	8	8	7	9	8	8	11	9.9
6	8	7	7	7	6	7	11	10.1
8	8	8	8	7	7	7+	11	10.6
10	9	9	10	7+	7	8+	10	10.5
12	9	8+	9	8	9+	9	10	10.3
14	10	9	10	9	9	9	11	10.4
16	10	10	9	10	10	10	12	-

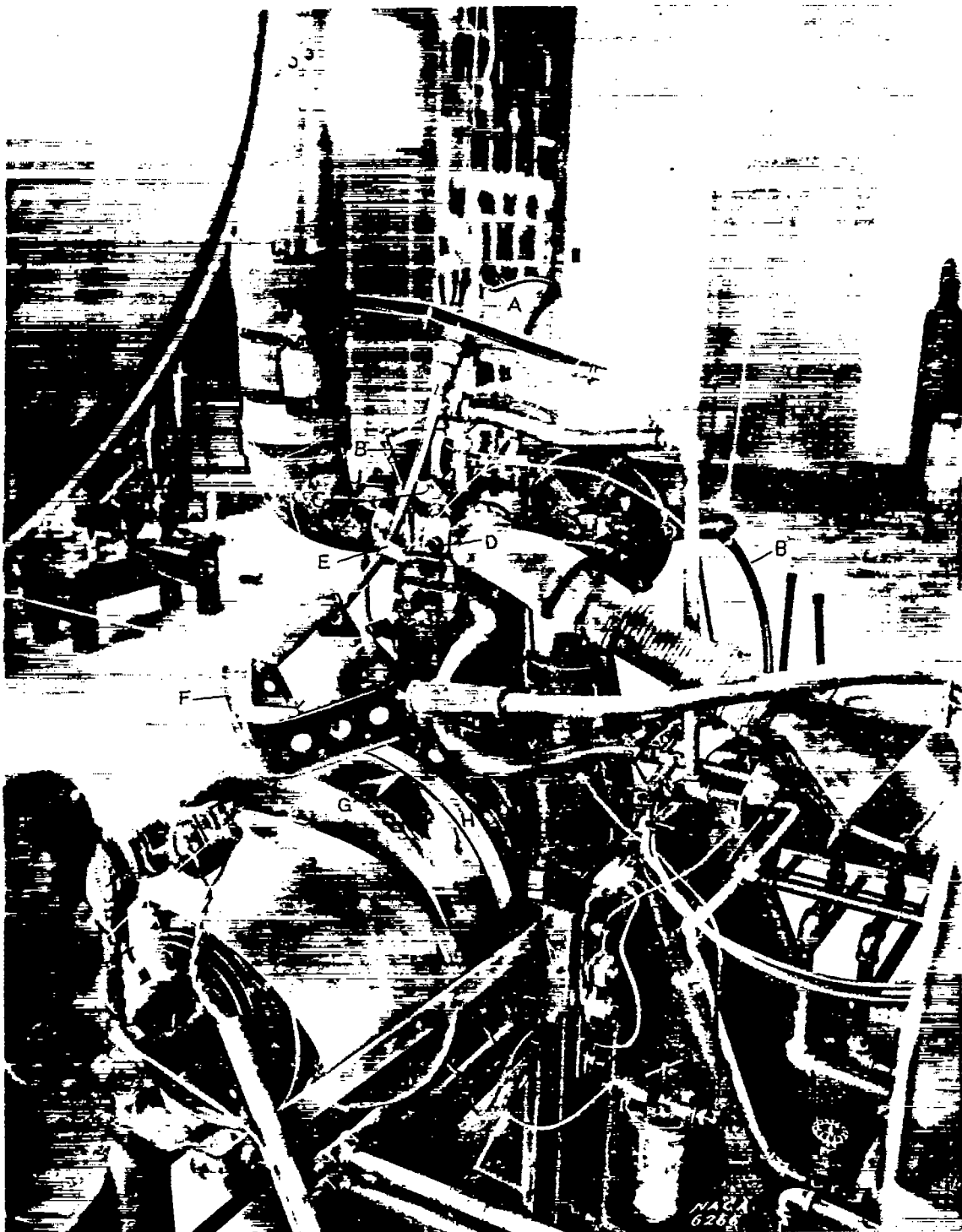


Figure 1.-Test engine with auxiliary apparatus.

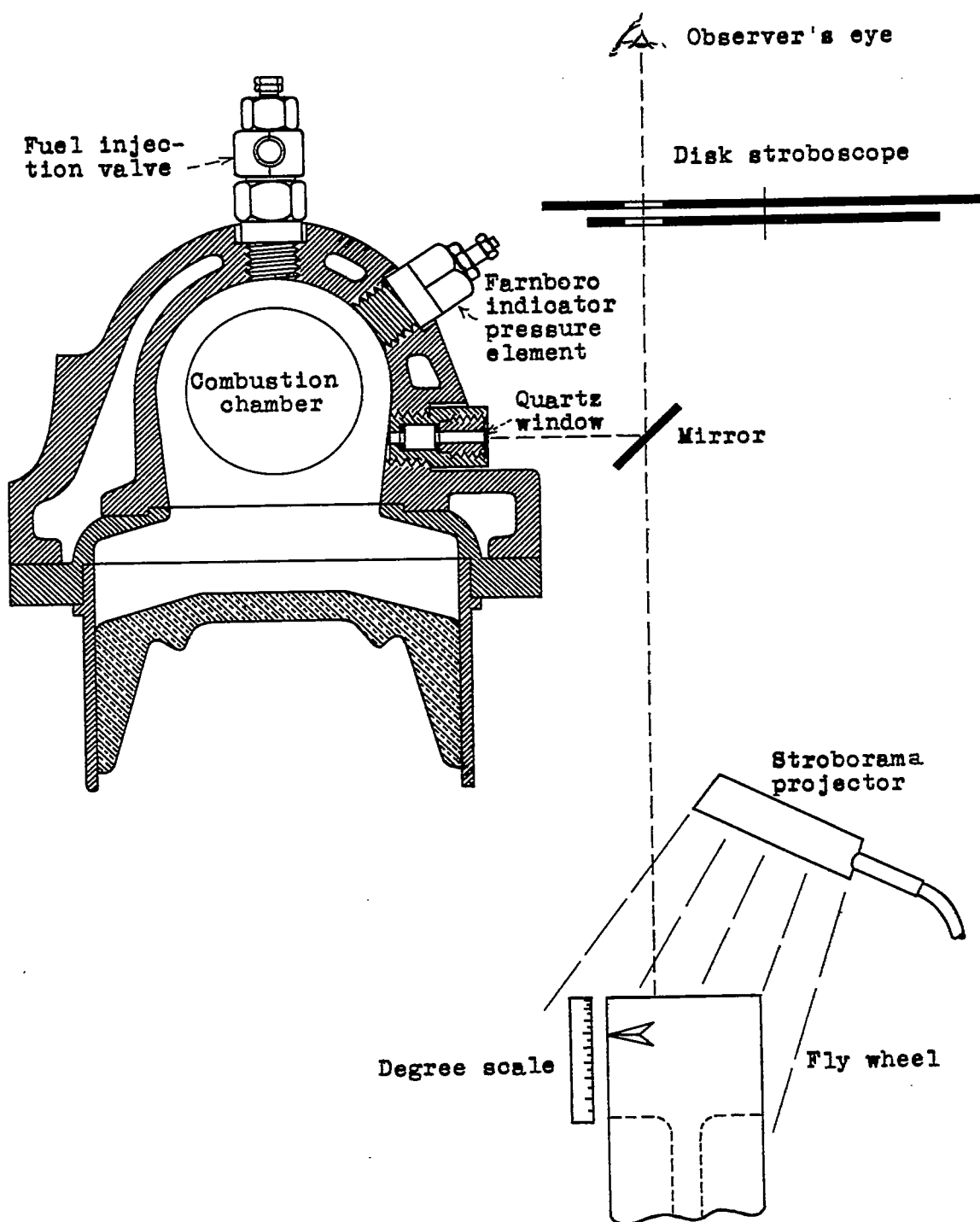


Figure 2.- Schematic diagram of relative positions of observer and apparatus when making simultaneous observations.

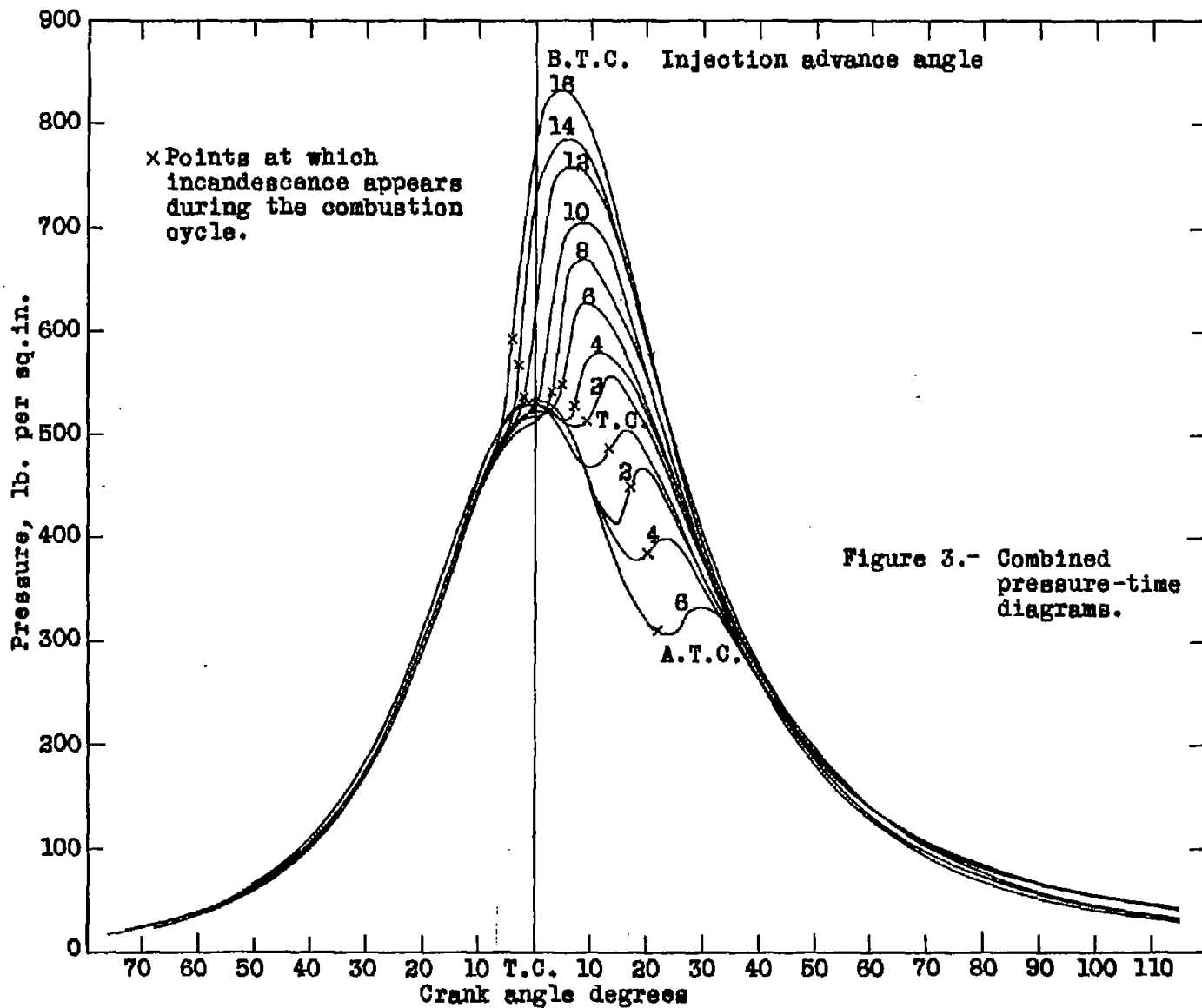


Figure 3.- Combined pressure-time diagrams.

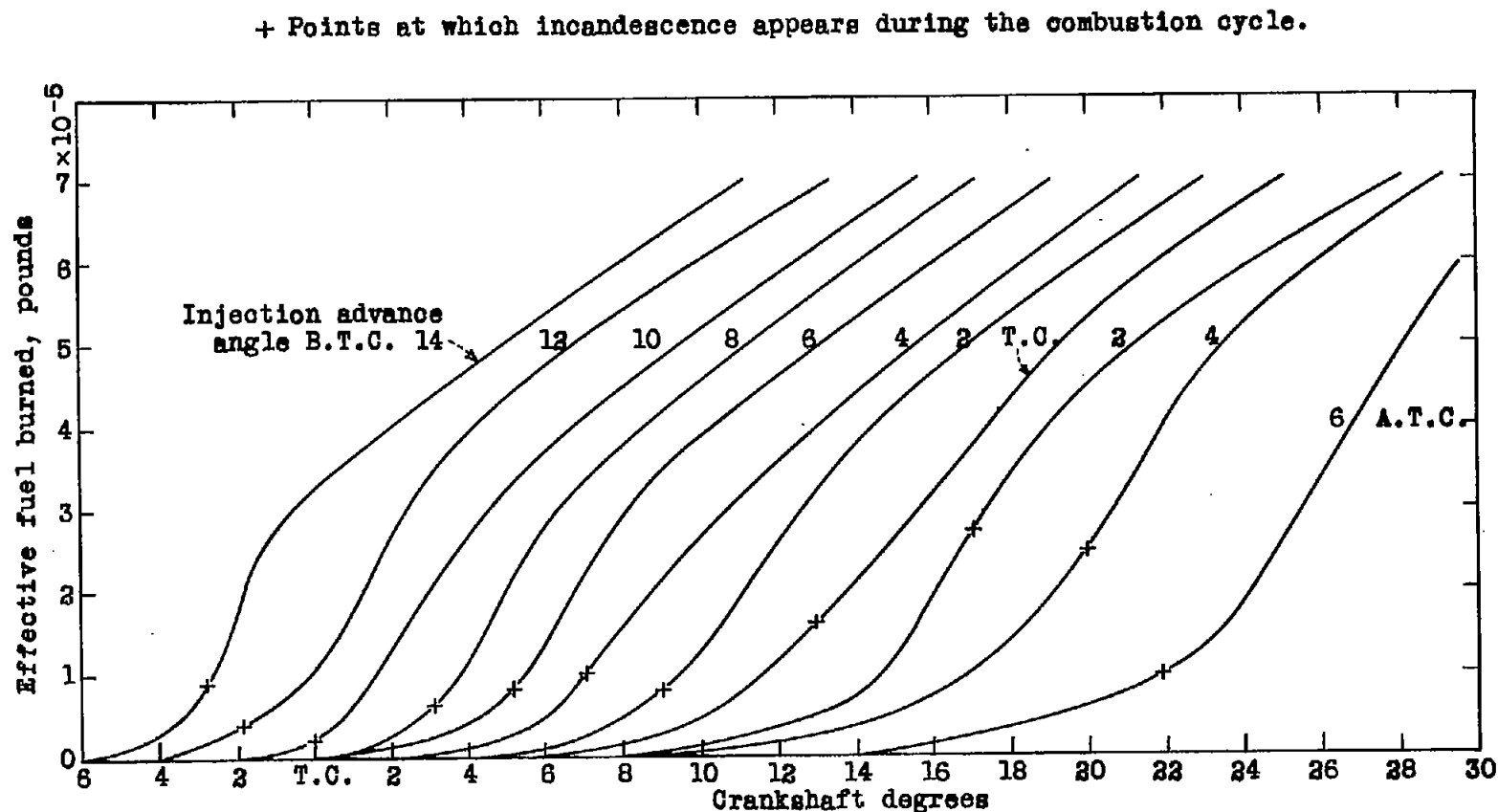
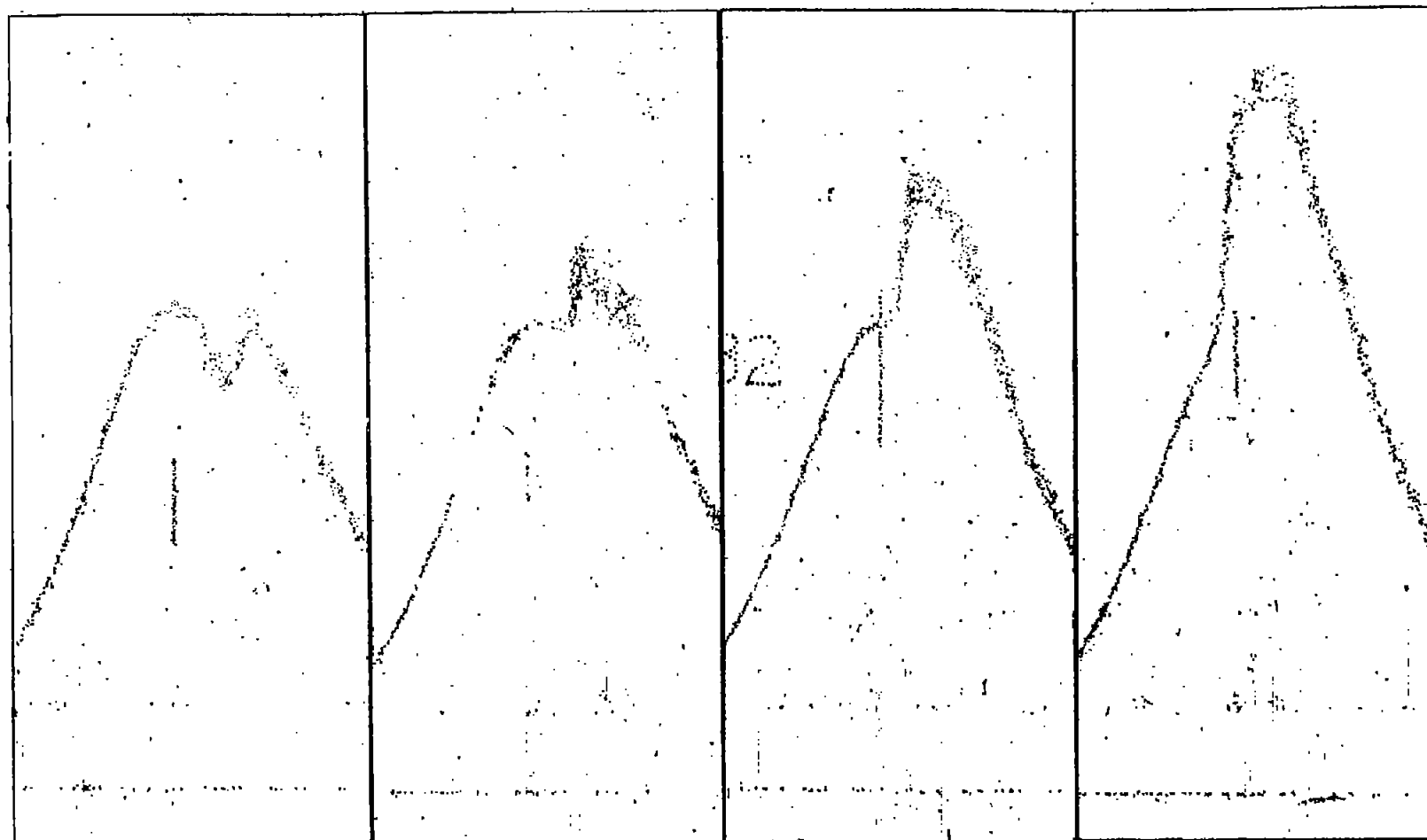


Figure 4.- Combined curves of effective fuel burned as determined by analysis of indicator cards.



I.A.A.:- T.C.

4° B.T.C.

8° B.T.C.

14° B.T.C.

Figure 5.-Typical pressure-time records  $\times \frac{1}{4}$ .  
Vertical line marks top center.